Femtosecond laser optimization of piezoceramic cutting

Y. DI MAIO, JP. COLOMBIER, E. AUDOUARD
Université de Lyon
Laboratoire Hubert Curien, UMR 5516 CNRS
Université Jean Monnet
42000 Saint-Etienne, France.

P. CAZOTTES
Groupe SAFRAN
75724 Paris, FRANCE

***Abstract*--Ablation characteristics of piezoceramics PZT have been investigated through femtosecond laser irradiation (120fs, 800nm, 5kHz, 0.2mJ) for industrial applications. First experiments demonstrate that unexpected features such as melting, microcracks, spallations or redeposition can damage the quality of the process and the performances of the final product. This work intends to quantify the ablation rate, the ablation threshold and the incubation phenomena to upgrade the quality of the industrial process. Optimizations based on ablation efficiency and visible nanostructurations are proposed.**

Keywords-Femtosecond laser; laser cutting; ablation threshold; ablation rate; incubation; ripples; Raman spectroscopy; piezoelectric; ceramic; PZT.

I. INTRODUCTION

Piezoelectric materials such as Lead Zirconate Titanate (PZT) are widely used for their mechanical properties in highly integrated systems. Fabricated from sintering methods, these materials present a hard but brittle polycrystalline layout which makes it difficult to cut. Furthermore its active response due to its non symmetric structure has to be unmodified by affected areas in the periphery of the processed zone. Usually, PZT ceramics are cut with automatic saws, creating stresses and microcracks due to the mechanical interaction. Here femtosecond lasers are used to develop a fast and reproducible cutting process and find the limits of such techniques in terms of reduced damage zone and high efficiency. They have a contactless interaction, a high adaptability for complex pattern machining on all materials and a very low thermal damaged area of few microns making it very efficient. This can be explained by the temporal duration of the pulses which allows multiphotonic excitation of band gap materials and which are also shorter than the thermal energy transfer time (some picoseconds) [1]. At this time scales, high peak intensities are reached producing very low collateral damage of the irradiated sample and preventing reposition of debris.

II. LASER SET-UP

The femtosecond laser used is based on a Ti:Sapphire crystal generating 0.2mJ pulses of 120fs and 800nm at a repetition rate of 5kHz. The beam is controlled by both an autocorellator for pulse duration and a beam analyzer for the spatial shape. The laser is focused through a fixed achromatic doublet on an 180µm thick PZT sample previously placed on x-y-z computered-controlled stages. The machining is then characterized with an optical microscope and a SEM for visual appreciations and tactile profilometry and confocal microscopy for depth measurements. The material structure is quantified with Raman spectroscopy but further analyses are needed for a better understanding of the results.

III. FIRST OBSERVATIONS

The variety of the experimental conditions, which have a drastic influence on the elementary process of interaction, add further complexity of the problem. Although most of the parameters are fixed in our experiments, unexpected results can still be induced: for instance, at energies higher than 6J/cm², PZT ceramics sometimes reveal spallations and microcracks supposedly due to structural modifications and laser induced residual stresses at the interface between the melted surface and the unaffected bulk. Adherent redeposition of matter sometimes pollutes the surface even after ultrasonic baths. Further metallisation for prospective applications can then become difficult. On the other hand, nanostructurations always perpendicular to the polarization appear at low energies (~100mJ/cm²) as it was mostly observed on metals (fig 1). On PZT, these so-called ripples seem to randomly erode the surface of the grains which results to a complete smoothing without paying attention to the brittle nature of the material. The orientation of the polarization on the efficiency of the cutting was also clearly

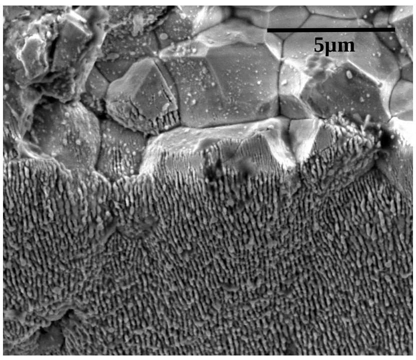

Figure 1. Ripples on a PZT sample irradiated at 232mJ/cm².

visible. Very rough grooves were observed for polarizations parallel to the cutting while smooth ones were machined with perpendicular polarizations.

IV. Specificities of the Laser-ceramic interaction

A. PZT characteristics

Lead Zirconate Titanate $Pb(Zr_xTi_{1-x})O_3$ is a solid solution of $PbZrO_3$ and $PbTiO_3$. It has an ABO_3 type perovskyte structure where A is occupied by Pb^{2+} ions and B by proportions of Zr^{4+} or Ti^{4+}. The Zr-Ti composition is responsible for the crystallographic phase of the material, from tetragonal Ti-rich region to rhombohedral Zr-rich region and a "morphotropic" phase in-between which exhibits superior piezoelectric properties [2]. Depending on this phase, the energetic band gap of this material oscillates between almost 2.9eV and 3.9eV, which involves a dielectric-like femtosecond interaction according to the wavelength used (1.55eV for 800nm). Contrary to metals, a first nonlinear absorption stage takes place during the laser excitation, promoting electrons from the valence band to the conduction band (3 photons absorption). Electron energy relaxation induces material ejection on longer time scales.

B. Ablation characteristics

For a better control of the femtosecond process, ablation characteristics of the PZT machining are investigated. Both impacts and grooves are machined with Gaussian shaped pulses. The ablation threshold was defined as the zero value of the ablated diameter according to the Gaussian equation and was estimated to be between 0.57 and 0.34J/cm² depending on the number of pulses used [3]:

$$F_{th} = F_{\max} e^{-\frac{1}{2}\left(\frac{D_a}{\varpi_z}\right)^2}, \tag{1}$$

$$D_a^2 = 2\varpi_z^2 \ln\left(F_{\max}\right) - 2\varpi_z^2 \ln\left(F_{th}\right). \tag{2}$$

Where F_{max}, F_{th}, D_a and ω_z are respectively the peak fluence, the threshold fluence, the ablated diameter and the beam diameter at a plane z.

The incubation coefficient ε is obtained by an empirical equation which states the evolution of the threshold fluence with the number of pulses N [4]:

$$F_{th}(N) = F_{th}(1)\ N^{\varepsilon-1}. \tag{3}$$

ε is equal to nearly 0.85 and close to most of the values calculated for metals with the same equation. It reveals a decrease of the threshold fluence with the pulses, which supposes that a high number of pulses weakens the solid and can involve a faster ablation. Static ablation rates show two typical regimes of ablation: the strong ablation followed by a saturation regime at higher fluences where hundreds of nanometers per pulse can easily be reached. The same study for non static ablation (from grooves rather than impacts) led to different results depending on the methodology used. Tophat approximations give rise to lower rates than Gaussian sampling but neither enables to recover the static one. This might be due to different incubation effects due to the variation of fluence as the beam shifts or the incident angles during the process leading to modifications of material absorption.

V. First optimizations

Nevertheless, first optimizations were tested for the cutting of PZT. Larger beam diameters with lower fluences were chosen to take advantage of the incubation effect and prevent non desired effects occurring at high fluences (wavefront distortion, air breakdown…). Low ablation rates at these fluences are largely compensated by the high number of pulses. Ripples on the edges of the cut testify of a low fluence interaction which minimize the heat affected area and redeposition of matter. For the quantitative analyse, Raman spectroscopy is employed to compare the surface structure between the irradiated area and the bulk. Typical spectra of crystalline PZT show peak intensities at wavenumbers corresponding to vibrational, rotational, and other low-frequency modes in the system. These peaks are very well identified on surfaces irradiated at low fluences, showing that the heat affected zone is very shallow. In contrary, flat spectra at high fluences suppose that amorphous PZT was formed deeper in the material.

VI. Conclusion

PZT materials are cut using femtosecond lasers so as to prevent microcracks and residual stresses from mechanical interactions of saws. However, similar bad results can occur if a wrong parametrization is adopted. Defining the characteristics of ablation and the nature of the interaction are the key points for a better controlled process. The ablation threshold and the ablation rate of our PZT revealed that lower fluences would not involve a loss of efficiency. In contrary, it requires a higher number of pulses in one scan, resulting in an increase of the quality of the cut due to a less affected surface, confirmed by Raman spectroscopy on ripples. Further studies will be considered to develop the specific paths of the industrialization of the process in identifying the optimal parameters to increase both the ablation rate and accuracy.

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